

behind the limb of the sun)<sup>9),10)</sup>. The flare of 5 December could quite reasonably have been from this same sunspot group, on its second time around. Activity died out after 5 December.

The PCD events of 10 November and 5 December do not seem to have been observed by other earth surface methods, although measurements made at Churchill<sup>11)</sup> of hydrogen emission from the night sky indicate the presence of considerably more hydrogen than normal on the nights of 10-11 and 11-12 November. LF recordings at very high latitudes seem to be the most sensitive method of detecting the presence of solar protons in the ionosphere by an earth surface experiment.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part I

## I-2-11. The Electron Density Profile of the Lower Ionosphere During a Polar Cap Absorption Event\*

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Polar cap absorption of radio waves is assumed to be caused by excess ionization produced by incoming solar protons. Taking a proton energy spectrum which appears to be fairly typical of these events, the resulting electron density profile is determined for both day and night conditions.

Assuming that the only species of negative ion in the lower ionosphere is  $O_2^-$ , the transition between day and night conditions is examined, and the electron density profile determined for solar zenith angles in the range from  $90^\circ$  to  $102^\circ$ . The vertical-incidence absorption of 30 Mc/s radio waves is evaluated as a function of solar zenith angle on the basis of this model. The theoretical prediction is compared with riometer measurements made during sunset conditions, and it is concluded that  $O_2^-$  is probably not the dominant negative ion in the lower ionosphere during twilight conditions.

Polar cap absorption of radio waves is now known to be caused by the ionization

produced in the lower ionosphere by an influx of low-energy solar cosmic rays. The flux and spectrum of these particles have

\* This paper was read by I. Paghis.

been measured directly on several occasions by balloon and rocket techniques, and it has been found that the integral energy spectrum can be represented over a wide range of energies by the relation  $N(>E) = KE^{-\gamma}$ , where  $N(>E)$  is the number of particles with energy greater than  $E$  and  $K$  is a constant. For the spectra measured from balloons during 1958-59, the exponent  $\gamma$  was generally found to have a value of about 4. The present paper is concerned with the electron density profile which such an incoming flux of cosmic rays would produce in the lower ionosphere, making the following assumptions:

- the particles are protons;
- they arrive at the earth isotropically from all directions;
- their energy spectrum is cut off sharply at some low-energy limit.

The first two assumptions are justified on the basis of the balloon observations, and the last assumption is merely one of convenience, since little is yet known about the low-energy characteristics of the spectrum.

The rate of production of electrons in the lower ionosphere has been calculated for an incoming flux of protons given by

$$N(>E) = 9 \times 10^8 E^{-4} \text{cm}^{-2} \text{sec}^{-1} \text{steradian}^{-1}$$

where  $E$  is measured in Mev; this value is based on balloon measurements made by Anderson and Enemark (1960) at Resolute Bay in July 1959. Two cases were considered, with low-energy cut-offs assumed to occur at (a) 20 Mev and (b) 40 Mev. The equilibrium electron density profiles were then calculated for daytime and night-time conditions using the method described by Bailey (1959), but employing more recent values of some of the atmospheric parameters. The equilibrium profile is found from the equations

$$q = an^2N + \alpha_d NN^+ - (kn' + p)N^- \quad (1)$$

$$0 = an^2N - \alpha_i N^- N^+ - (kn' + p)N^- \quad (2)$$

$$0 = N^+ - (N + N^-) \quad (3)$$

where  $N$ ,  $N^+$ , and  $N^-$  are respectively the electron, positive ion and negative ion densities (all negative ions being assumed to be  $O_2^-$ ),  $n$  and  $n'$  are the  $O_2$  molecular number density and the total molecular number density respectively, and  $q$  is the rate of production of electrons by the incoming

proton flux. The other atmospheric parameters are listed below, together with their adopted values and the sources of these values:

$$a = \text{attachment coefficient for } O_2 = 1.5 \times 10^{-30} \text{cm}^6 \text{sec}^{-1}$$

(Chanin, Phelps and Biondi (1959));

$$\alpha_d = \text{dissociative recombination coefficient} = 3 \times 10^{-8} \text{cm}^3 \text{sec}^{-1}$$

(Bailey (1959));

$$k = \text{effective collisional detachment coefficient} = 2 \times 10^{-17} \text{cm}^3 \text{sec}^{-1}$$

(Bailey and Branscomb (1960));

$$p = \text{photodetachment coefficient for } O_2^- = 0.44 \text{sec}^{-1}$$

(Smith, Burch and Branscomb (1958));

$$\alpha_i = \text{ionic recombination coefficient} = 10^{-7} \text{cm}^3 \text{sec}^{-1}$$

(Nicolet and Aikin (1960)).

The equilibrium electron density profiles for the 40 Mev cut-off are shown in Fig. 1,

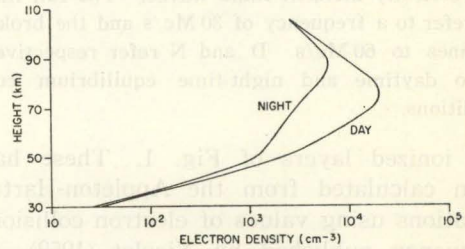


Fig. 1. Height profiles of electron density during daytime and night-time equilibrium conditions for a low-energy cut-off value of 40 Mev.

where it can be seen that the daytime peak lies at about 75 km; at night, this peak rises to about 85 km. For the case of a 20 Mev cut-off, the profiles are very similar in form, though the actual values of electron density are considerably higher. The reason for this insensitivity of the shape of the profile to the spectrum cut-off lies in the rapid increase in atmospheric density with depth and the form of the range-energy relation for protons in air. It can readily be shown that the profile shape is also insensitive to the form of the proton spectrum. Davis, Fichtel, Guss and Ogilvie (1961) have published the results of a spectrum measurement made by rocket techniques at Churchill on September 3, 1960. This spectrum extended down to 13 Mev and, unlike the spectrum

we have been considering, could not be described by a simple power law. The daytime electron density profile has been calculated for this spectrum, and was found to be very similar to that shown in Fig. 1, having a maximum at 75 km.

Fig. 2 shows the specific absorption profiles for vertically incident 30 Mc/s and 60 Mc/s radio waves which would be produced by

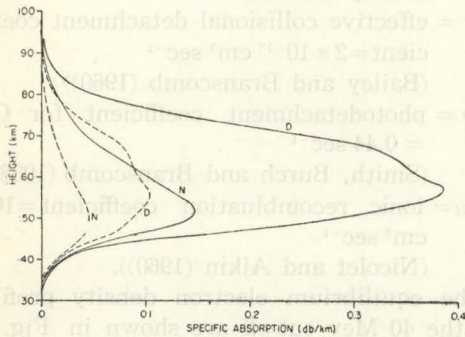


Fig. 2. Height profiles of specific absorption for vertically incident radio waves. The full lines refer to a frequency of 30 Mc/s and the broken lines to 60 Mc/s. D and N refer respectively to daytime and night-time equilibrium conditions.

the ionized layers of Fig. 1. These have been calculated from the Appleton-Hartree equations using values of electron collisional frequency published by Nicolet (1959). At 30 Mc/s the maximum absorption is seen to occur in the 55-60 km region during daytime and in the 50-55 km region at night. The ratio of daytime to night-time absorption at 30 Mc/s is about 3; this is somewhat lower than that usually observed by riometers, suggesting that the collisional detachment coefficient which we have adopted ( $2 \times 10^{-17} \text{ cm}^3 \text{ sec}^{-1}$ ) is too large. A value of about  $1.5 \times 10^{-17} \text{ cm}^3 \text{ sec}^{-1}$  would give a rather better fit with these observations.

One of the most striking features of a PCA event is the well-marked transition at twilight between daytime and night-time conditions. During evening twilight, the daytime absorption starts to decrease at about the time of ground sunset, and night-time equilibrium is reached when the shadow of the solid earth reaches a height of about 50 km. The reason for the decrease is the increase in the number of negative ions when photodetachment does not operate.

These negative ions are usually assumed to be mainly  $\text{O}_2^-$ , with some  $\text{O}^-$  at higher altitudes, since  $\text{N}_2$  does not form a stable negative ion. Based on this hypothesis, but ignoring the presence of  $\text{O}^-$ , an attempt has been made to compute the expected variation of absorption with solar zenith angle during this transition period. The results of this investigation will now be briefly described.

According to Phelps and Pack (1961)  $\text{O}_2^-$  has an electron affinity of 0.46 eV, which implies that the entire visible spectrum of sunlight should be capable of producing photodetachment. Smith, Burch and Branscomb (1958) have made laboratory measurements of the differential photodetachment coefficient as a function of wavelength, and their results show that, when the distribution of energy in the solar spectrum is taken into account, the important wavelength region is from 0.3 to 1.2 microns. At large zenith angles, the energy reaching a given point in the ionosphere will be gradually reduced by scattering, absorption and refraction in the lower atmosphere before the sun actually sets below the horizon. This will result in a steady decrease in the photodetachment coefficient, rather than a sharp cut-off when the solid earth shadow reaches the height in question. This variation in photodetachment coefficient with solar zenith angle has been calculated using relations developed by Hunten (1954) in connection with the sodium twilight problem. Three effects have been considered:

- Rayleigh scattering;
- absorption of visible sunlight by the diffuse Chappuis bands of ozone;
- dilution by refraction.

Some typical resulting curves of photodetachment coefficient as a function of wavelength are shown in Fig. 3. The heights quoted for the individual curves refer to the closest approach which the sunlight makes to the surface of the earth before it reaches the point in question. The curve labelled 40 km is very close to the curve of Smith, Burch and Branscomb for unattenuated sunlight; the prominent dip which develops as the ray approaches closer to the earth is due to ozone absorption. The shift of the curve towards the red end of the spectrum is very noticeable at very low angles.

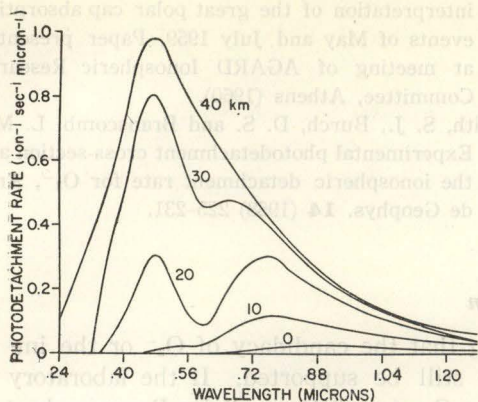


Fig. 3. Calculated differential photodetachment rates for various values of the closest approach of the ray to the earth's surface.

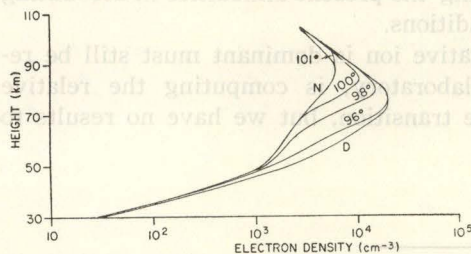


Fig. 4. Calculated height profiles of electron density for various values of solar zenith angle. D and N refer respectively to daytime and night-time equilibrium conditions.

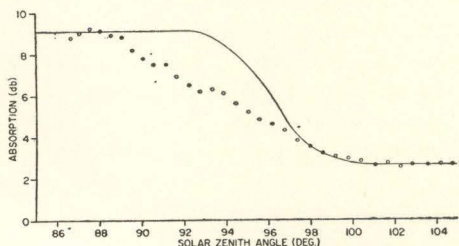


Fig. 5. Vertical 30 Mc/s cosmic noise absorption at Churchill during sunset twilight on November 13, 1960. The curve shows the calculated variation of absorption.

These curves have been integrated to find the total photodetachment coefficient, and these values have been used in equations (1) and (2) above to determine the electron density profiles for various solar zenith angles. Some of these profiles are shown in Fig. 4, which also includes the equilibrium daytime and night-time profiles. Using these profiles, the 30 Mc/s vertical ab-

sorption has been calculated as a function of solar zenith angle. The result is shown in Fig. 5, together with the sunset values measured by a riometer at Churchill during the event of November 12-13, 1960. The agreement between theory and experiment is obviously very poor. The transition is more gradual than theory predicts, and starts at a zenith angle of about  $89^\circ$ , instead of the predicted  $93^\circ$ . Comparisons made at other times show similar results, and this lends support to an earlier suggestion by Reid and Leinbach (1960) that the dominant negative ion during twilight in the lower ionosphere is not  $O_2^-$ , but some ion which requires ultraviolet light rather than visible light for efficient photodetachment. The effective shadow for such an ion would be that of the ozone layer rather than of the solid earth, and the shadow effect would become noticeable at smaller solar zenith angles. The nature of this ion is as yet undetermined, though Reid and Leinbach have suggested that  $O_2^-$  or  $NO_2^-$  may play an important part. This latter ion has been detected in surprisingly large quantities at higher altitudes during rocket mass spectrometer flights reported by Johnson, Heppner, Holmes and Meadows (1958).

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### Discussion

**Bailey, D.K.:** It is perhaps worth suggesting that the candidacy of  $O_2^-$  or the important negative ion in the PCA effect can still be supported. If the laboratory measurements for the photodetachment rate for  $O_2^-$  ( $\rho_s=0.44 \text{ sec}^{-1}$ ) by Branscomb *et al.* were measurements of detachment for excited states of the ion, whereas the  $O_2^-$  formed during PCA's is mostly in the ground state, then it may be suggested that ultra-violet light is required for the ionospheric photodetachment. Such a suggestion, if correct, might go some way toward explaining the present difficulties in accounting for the absorption changes during twilight conditions.

**Paghis, I.:** Yes, the question of which negative ion is dominant must still be regarded as open. Dr. Luise Herzberg, of our laboratory, is computing the relative populations of  $O_2^-$  and  $NO_2^-$  during the sunrise transition, but we have no results to date.

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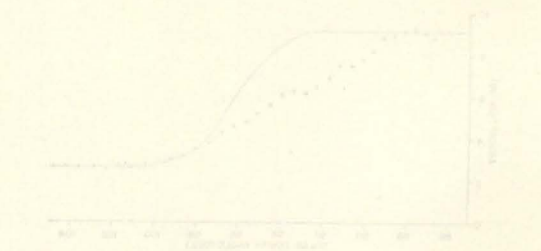


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